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Development of a device for restoration of the flowability of caked fertilizers with justification of its design and operating parameters

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Abstract. The article explores the possibility of use of a separate two-phase technology in agriculture to restore the flowability of caked mineral fertilizers. Flowability is one of the most important properties of fertilizers that determine their quality during storage and transportation. Flowability is understood as the property of a mineral fertilizer to flow freely under the influence of gravitational forces. Under certain environmental conditions, fertilizers may cake. To solve this problem in the preparation of fertilizers at agricultural enterprises, a new design of a preliminary grinder is proposed as a part of a two-phase technology. Based on the results of the experimental studies, the most rational design and operating parameters of the grinder have been determined. Practical recommendations on the possible use of the developed drum-type grinder for the destruction of other brittle materials in preparation for their introduction into the soil at agricultural enterprises are formulated.

1 Introduction

Mineral fertilizer is a fertilizer of industrial or fossil origin, containing nutrients that are used in agriculture in a mineral form [1,2,10,16]. Caking is the property of a mineral fertilizer to form phase adhesion contacts between grains till formation of a solid monolithic mass. Such an agglomerate is formed as a result of residual moisture in the commercial product, heterogeneous and different mechanical strength of the granules, and hygroscopicity. Caked

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fertilizers do not allow them to be unloaded from transport containers, impede the operation of mechanical mixing and fertilizer dosing devices, which disrupts the continuous technology of their implementation and use.

In this regard, before preparing and applying mineral fertilizers to the soil at agricultural enterprises, it is necessary to restore the flowability of caked agglomerates using mechanical destruction [15,18]. To implement this, special grinding devices are used [3].

2 Problem statement

Devices with working elements in the form of knives, rolls, chains, cutters are used in agriculture, in machines for grinding of caked mineral fertilizers commercially produced earlier and currently. In this machines the material is destroyed due to grinding, fracture and abrasion [4]. Studies show that caked mineral fertilizers are brittle and relatively soft materials, and therefore, for their grinding, it is advisable to use devices that implement such methods of impact on the grinded material as cleaving and rupture [5].

Practice shows that none of the modern devices can grind the product to a monodisperse state. At the outlet, large inclusions and a dusty fraction with a granule size of less than 1 mm inevitably come across. Regrinding of granules occurs as a result of irrationally and poorly controlled destructive loads, from the properties of caked fertilizers. A high content of fine dusty fraction can lead to repeated caking during storage, to formation of arches in bunker tanks, to an increase in the uneven distribution of fertilizers during their application [6,7].

3 Research questions

One of the reserves for improvement of the qualitative preparation of caked mineral fertilizers for use is the proposed two-phase machine grinding technology. The essence of the technology lies in the sequential grinding of large caked pieces of fertilizers to the required fractions using different devices. According to this technology, the devices for the first and second phases of grinding the caked blocks of fertilizers are adjusted to their fineness range. This allows to destroy the material of each size group with a gentle impact, and to sort out the dusty fraction after each phase of grinding. The advantages of two-phase technology also include a reduction in the energy intensity of production unit processing.

Today, operations for grinding caked fertilizers are carried out on one device. Such operational diagram does not provide the required indicators for the quality and energy intensity of the process of caked fertilizers grinding.

4 Materials and methods

The pre-grinder can be a very promising technical solution as the first phase of grinding of caked mineral fertilizers. In the separate grinding of caked materials, such devices largely determine the efficiency of restoring the flowability of caked fertilizers. For this purpose, a drum-type grinder has been developed. The design of this crasher is shown in Figure 1, its technical characteristics are shown in Table 1 [8].

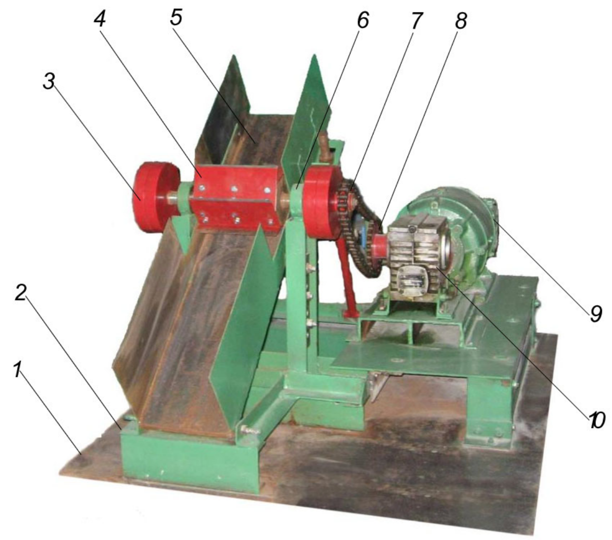

Fig. 1. Drum-type grinder used in two-phase technology for restoration of the flowability of caked fertilizers: 1 - foundation; 2 - frame; 3 - flywheel; 4 - drum with blades; 5 - tray; 6 - racks; 7 - small star wheel; 8 - big star wheel; 9 – electric motor PM-32M; 10 - worm gearbox 2CHM-63; 11 - elastic coupling; 12 - damper element; 13 - screw pair; 14 - chain drive; 15 – swivel.

Table 1. Device Specifications.

Options	**Meaning**
Productivity for 1 hour of main time, t/h	3
Energy intensity of processing a ton of products, kWh / t	0.25
Re-grinded fraction, % not more than	2
Drum: Length, mm Diameter, mm Weight from the drum, kg Weight of removable flywheels, kg Maximum speed, rpm Drum shape	 200 120 20 20 120 hexagon
Chopping knives: Length, mm Thickness, mm Blades overhang, mm Number of blades, pcs.	 200 4 45 6
Tray: Width, mm Length, mm Thickness, mm	 210 1000 16
Overall dimensions, in mm Length Width Height	 1000 900 600
Weight (with foundation), kg	250
Electric motor power, kW	2.2

5 Results

The process of operation of proposed device is as follows. The material to be grinded enters the working chamber formed by the radial blades of the drum 4 and the area of the corrugated surface of the tray from the hopper through the tray 5. When caked fertilizers interact with sharp-pointed blades, the material is destroyed [9]. The destruction of the caked material by the blades of the drum to the desired fineness is shown in Figure 2.

The material is destroyed into incoherent parts by the splitting-grinding action of the blade and the edges of the blades. The width of the blades is consistent with the overall dimensions of the tray. Depending on the physical and mechanical properties of the caked fertilizers, the shape of the blades can be different (straight, wedge-shaped, toothed). Each of six blades is attached to the sides of the hexagonal drum using six bolts.

a) b)

Fig. 2. Destruction of caked material: a) sharp-pointed blades of the drum; b) the edges of the drum blades.

Discharge of grinded material from the area of impact is intensified by the air flow of the drum and the inclination of the tray. Large fractions are sent for regrinding, small ones are calibrated by perforated holes in the bottom of the tray. A spring damper is provided in order to prevent the overload of the device from hitting a non-grindable body.

Depending on the properties of the grinded material and the required size class, the device allows to set the following parameters: the drum rotation speed, the angle of the tray, the shape of the blades. The optimal operating mode of the grinder, established during preliminary tests, is shown in Table 2. To increase the throughput of the grinding device, the working plates can be equipped with spikes or cutters mounted in a checkerboard pattern on the edges of the blades. Additional cutting elements will also reduce the adhesion of the hygroscopic material to the surface of the blades.

Table 2. Drum grinder operational mode.

Blade shape	Blades speed, m/s	Tray inclination angle, degrees
toothed	0.3...0.6	37.5...42.5 ^{0}

While adjusting the grinder to the set parameters and operating modes, the productivity is 1.62 ... 1.87 t/h for ammonium nitrate, 1.8 ... 2 t/h for urea. The energy consumption of processing a material unit does not exceed 0.21...0.24 kWh/t for nitrate, 0.14...0.19 kWh /t for carbamide, which is less compared to regular grinders.

6 Discussion

The process of grinding of caked granular fertilizers is associated with overcoming the cohesive forces between the particles, which requires a very large amount of mechanical energy. In the general case, the amount of energy required for destruction depends on many factors: strength, shape, size, relative position, heterogeneity of the structure of the grinded bodies, the degree of product grinding, the type of contact of the working body with the caked medium, etc.

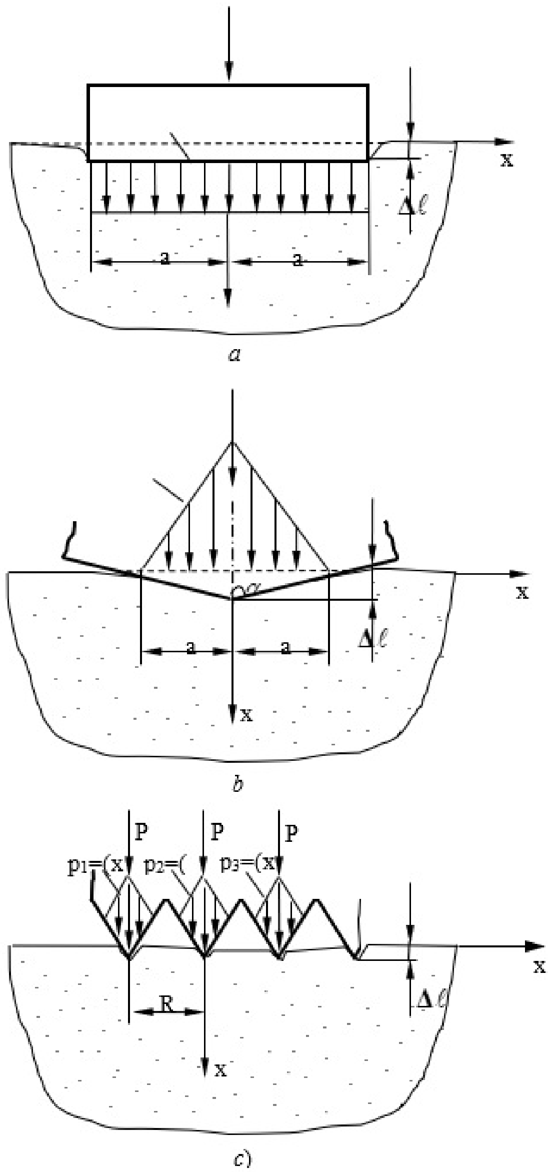

Fig. 3. Contact interaction of the grinding knife with the studied material, for different forms of working surfaces: a) straight blade; b) curved blade; c) serrated blade.

When calculating, special attention should be paid to the mechanics of the contacting bodies of the working body (elastic medium). The working body (knife) of the developed grinding device is a flat plate made of structural alloy steel.

Most often in engineering practice there are knives with a contact area with a shape of: a straight blade, a curved blade, a toothed blade [11]. Based on this information and our own observations, the above working surfaces have been taken for theoretical analysis (Figure 3).

The interaction of each of these contacts with a caked brittle medium shall be considered making the assumption that only the normal surface force is in place (it will not have a significant effect on the choice of the most rational blade shape).

First, a knife with a base in the form of a straight blade shall be studied (see Figure 3a). The straight line of the blade (knife length) is directed in parallel to the x1 axis and has a thickness of b+b along the x2 axis. Since the dimensions of the caked medium are large compared to the contact area of the knife, then, with a sufficiently good degree of approximation, the rectangular profile of the contact area can be replaced by an elliptical surface of similar dimensions. Then, to determine the displacements and stresses in an elastic granular medium, the classical Hertz approach on the contact of solid bodies can be used [12,13,14].

Following Hertz, the well-known expression is used to determine the critical displacement of the knife blade in the area of plane deformation.

For a knife with a length of 200 mm and a width of 1 mm, eccentricity is equal to e = 0.994987≈1, then, taking into account the fineness of the grinded product, the consumption of grinding work per one rotation of the drum is expressed by the formula:

$$A_1 = \frac{3}{2}\frac{P}{\pi a^2\sqrt{1-e^2}}K_d\left[\frac{3P}{4\pi a\left(\frac{1-\nu_1}{G_1}+\frac{1-\nu_2}{G_2}\right)}\Lambda + \frac{\Lambda-1}{4}e^{r^2} + \right.$$
$$\left. + \frac{9}{64}\left(\Lambda - \frac{7}{6}\right)e^{r4\frac{25}{256}\left(\Lambda-\frac{37}{30}\right)e^{r6}]}\frac{1}{2l\,Vk\,i}\right], \quad (1)$$

where P is the surface force, N;

a is a semi-major axis of the ellipse, m;

ν_1, ν_2 are Poisson's ratios of the tested material and knife;

G_1 , G_2 are shear modules of the deformable material and knife, N/m ^{2};

E_1, E_2 are Young's modules of the tested material and working body, N/m ^{2};

i is volumetric degree of grinding, approximately equal to 5;

l is the maximum thickness of the grinded fraction, m;

k is the number of knives installed on the drum, pcs ;

$\Lambda = \ln\frac{4}{e}$ is the constant;

$e' = \sqrt{1-e^2}$ is an additional module;

K_d is dynamic coefficient, (4…5) [17].

After that the introduction of a knife with a curved blade shape into the tested material shall be considered (see Figure 3b). In the Figure, the length of the curved blade (along the width of the tray) with the contact area of a+a is directed along the x_2 axis.

To describe the critical stress state of a brittle body from the introduction of a curved blade, the equation from the theory of elasticity shall be used [11,12]:

$$\sigma = 0.388\sqrt[3]{PE_1^2\frac{1}{R^2}}K_d \quad (2)$$

where R is the radius of blade curvature, m.

The radius of blade curvature is set from the conditions of penetration of the knife into the tested material. In order to ensure that the deformations are small enough to remain within the framework of the linear theory of elasticity, the half-angle of the wedge shall be 80...90^0.

The work of grinding of the material in one rotation of the drum with a curved blade shall be found taking into account the degree of grinding of the product from the following expression:

$$A_2 = \left(0{,}388\sqrt[3]{\mathrm{PE}_1^2 \frac{1}{R^2}}\right)^2 K_d \frac{V}{2E_1} ki, \quad (3)$$

Now the case when the loaded area of the knife is a toothed blade shall be considered (see Figure 3c). One element of the toothed surface behaves like a curved blade, however, the work of the set of teeth differs significantly from the work of the wedge, since there is an interaction of stresses that occur in the area of contact between the knife teeth and the studied material.

For the convenience of mathematical analysis using the Saint-Venant principle, the pressure distribution from the action of the jagged surface shall be replaced with the pressure distribution from the force acting along the line along the surface of the body [13,14,15]. Such loading can be otherwise represented as the indentation of a straight knife blade into the body along the x_1 axis (Figure 4).

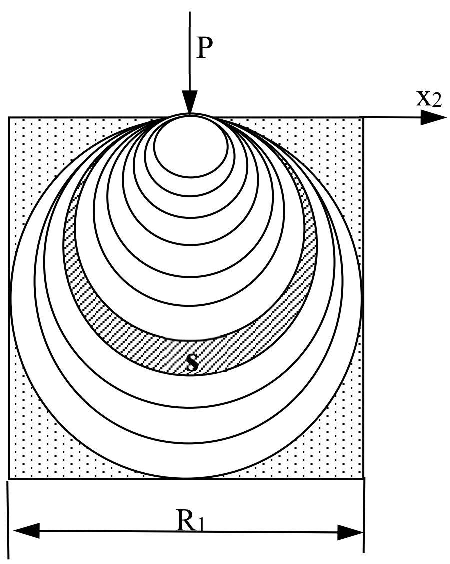

Fig. 4. Diagram of stress distribution (according to Flaman) in a fertilizer sample when a straight blade is pressed in.

In the Figure, the isolines of the stresses emanating from the point of application of the force are shown as circles. According to Flaman, the stresses arising on such circles are homogeneous and can be determined by the following expression [13]:

$$\sigma = \frac{2K}{\pi r}, \quad (4)$$

where r is a circle diameter, m;

K is the force distribution along the straight line, N/m.

$$K = \frac{P}{R_2}, \quad (5)$$

where $P$is the surface force, N;

L is the length of the force application line, m.

From Figure 4, the circles define the cylinders, between which the material is enclosed, the work of deformation of which, according to Kick, is equal to:

$$A = \frac{\left(\frac{2K}{\pi r}\right)^2 \frac{\pi r_1^2 - \pi r_2^2}{4} L}{2E_1}, \qquad (6)$$

where $\frac{\pi r_1^2 - \pi r_2^2}{4}$ is the area between close circles, m ^{2}.

The interaction of the blade with the studied material occurs over a very small contact area, while the destruction occurs "without visible deformation", therefore the friction forces that arise are quite small. It made it possible not to take them into account in the calculations.

An analysis of the obtained theoretical dependencies shows that the energy intensity increases with increasing the drum speed. Therefore, to reduce the energy consumption, it is advisable to reduce this parameter. Energy consumption also depends on the shape of the work surface. With a toothed surface, the grinding process is accompanied by the least energy consumption.

7 Conclusion

Thus, theoretical studies of the operational process of the grinding device proposed for implementation at agricultural enterprises made it possible:

- to justify the structural and operational scheme of the device;
- to justify the shape, length and diameter of the drum;
- to set the most rational overhang of the grinding knives;
- to study the influence of the shape of the working surface on the power and energy intensity of the grinding process.

The technical novelty of the device is confirmed by the utility model patent No. 231257 [9]. Distinctive features of the grinder are: the multifaceted shape of the drum with fastening of pointed blades with the possibility of their removal and replacement, the configuration and location of the blades on the drum, the pusher for supplying material to the impact zone. The proposed device can work both in a production line for restoration of the flowability of caked fertilizers at agricultural enterprises, and as an independent device for grinding brittle materials.

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